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Modeling and Analysis of Superconducting Fault Current Limiters Applied in VSC-HVDC Systems

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Abstract—Direct current transmission based on Voltage Source Converters (VSC-HVDC) has a number of advantages compared with traditional HVDC systems. However, VSC-HVDC systems are subjected to high short circuit currents due to faults in the DC line, which may contribute negatively to the dissemination and advances of this technology. In this context, this paper analyzes the impact of superconducting fault current limiters on the system response due to faults in the DC line. An effective model for fault limiters is proposed, aiming at limiting the fault current to values below the short circuit withstand capability of DC breakers. The results show the effectiveness of the method and the advantages of using superconducting materials to minimize the impact of faults on VSC-HVDC lines.

Keywords— Fault current limiters, HVDC, superconducting materials, VSC-HVDC.

I. INTRODUCTION

The majority of existing direct current (DC) transmission systems in the world is based on current source converters (CSC-HVDC), which are suitable for transmitting high levels of power over long distances. However, despite being a well-established technology, the CSC-HVDC systems offer low power flow control flexibility, which limits their use to the point-to-point applications with high levels of power capability [1-2].

Another technology for DC transmission is based on voltage source converters (VSC-HVDC), which employ, generally, Gate Turn-Off (GTO) or Insulated Gate Bipolar Transistors (IGBT). With advances in power electronics, this technology has been used widely in many countries across the world, especially in North America and Europe [3]. VSC-HVDC systems have advantages over CSC-HVDC systems, such as: they allow independent control of the active and reactive power flow, allow the connection of the converter to a weak AC system, employ more compact and cheaper filters, use lighter cables and, mainly, allow multi-terminal applications [4-6]. In this context, the

advantages of VSC-HVDC systems in relation to other types of transmission systems, coupled with technological advances in power electronics are motivating researchers around the world to study these systems [1-6]. However, the high fault current levels in the DC lines can limit the use of this technology [4]. Thus, the studies related to the protection system VSC-HVDC lines are necessary.

The CSC-HVDC systems have the natural ability to withstand short circuit currents in the DC lines, because of the inductors in series with the line. In contrast, VSC-HVDC systems do not employ such inductors, reducing their capability to withstand overcurrents in comparison with the CSC-HVDC technology [4-6]. Another issue to be analyzed for faults in the DC line is that for multi-terminal applications, the use of DC breakers is necessary, and these devices have low short circuit capability, reaching about 9 kA [4]. Thus, the protection for VSC-HVDC systems must be fast enough to clear the fault before the current exceeds the equipment limits. In order to mitigate the effects of fault currents in VSC-HVDC systems, superconducting fault current limiters (SFCL) were proposed as a potential solution to significantly minimize the impact of high fault currents and improve system stability during fault conditions [7-9]. These studies proved the effectiveness of SFCL in limiting the fault current in HVDC lines. However, the design features of SFCL have not been presented and the effects of DC breakers have not been considered.

Therefore, this paper proposes an effective model for superconducting fault current limiters (SFCL) used in VSC-HVDC systems. The SFCL is made of first generation high temperature superconductors (HTS). The paper will analyze the impacts of the proposed SFCL on the VSC-HVDC systems, considering the presence of DC breakers. The results demonstrate the effectiveness of using SFCL to control the fault level.

This work was organized as follows: Section II addresses the SFCL modeling by using the RSCAD software [10]. Section III

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presents the two-terminal VSC-HVDC system used in this paper. In Section IV the effective model methodology for SFCL is presented. In the Section V the results are shown and Section VI covers the main findings of this work.

II. MODELLING OF RESISTIVE TYPE SFCL

The levels of short circuit currents in power systems have shown significant growth in recent decades. Such high fault currents can damage important equipment through electromechanical efforts and/or thermal stress [9]. An alternative to keep the fault current below these limits is the installation of fault current limiters (FCL) at appropriate locations [11].

Basically, an FCL consists of a variable impedance. In a fault situation, this impedance increases, causing the current to decrease to levels below the breaker limit. Thus, an FCL should have low impedance under normal operating condition and high impedance under fault conditions. The FCL applications in power systems not only limit the magnitude of fault current but also enhance the stability margins of the system [11].

Superconducting fault current limiters meet the requirements stated above, with the advantage that they present rapid transition from superconducting state to fault state and quick recovery back to the superconducting state after the fault clearance [7-9]. In addition to their intrinsic safety and capacity of self-restoration, these devices have negligible influence during the power system normal operation and effectively reduce the short-circuit currents. Among the types of SFCL, the resistive type has been employed worldwide, due to its simplicity, low weight and volume [7-8]. Thus, this is the SFCL type investigated in this work. The performance of an SFCL is dominated by the interaction between HTS (High Temperature Superconductors) electromagnetism and thermal physics. The most important electromagnetic property of an SFCL is the relationship between electrical field and current density, which is also known as E-J Power Law of HTS.

In this paper, the RSCAD model of a resistive type HTS SFCL was developed by using the C-Builder tool, which allows detailed modeling of the superconducting material in C programming language. The value of the DC current in the line is the input signal of the model and the output signal controls a variable resistance. The model implemented in this work is based on the mathematical formulation presented in [11] and [12], which is briefly described below.

For the first generation HTS ($\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+x}$), known as Bi2223, the relationship between the electric field and the current density can be divided into three different physical equations, which respectively represent the superconducting state (the resistance of the material can be neglected), the flux-flow state and the conducting state. The behavior of each state is given by (1).

$$E = \begin{cases} 0 & T < T_c \text{ and } J \leq J_c - \text{"SC state"} \\ E_c \cdot \left(\frac{J}{J_c}\right)^{n(T)} & T < T_c \text{ and } J > J_c - \text{"flux-flow"} \\ \rho(T_c) \cdot \left(\frac{T}{T_c}\right) \cdot J & T \geq T_c - \text{"conducting"} \end{cases} \quad (1)$$

wherein E_c and J_c are the critical electric field and critical current density, respectively, ρ is the specific resistivity of the material and T_c is the critical temperature of the HTS. According to experimental results for materials of the type Bi2223, the exponent n can vary within a range from 10 to 20 [12].

The transition from superconducting state to conducting state usually takes place very quickly, so adiabatic condition can be applied in the model to neglect the heat transferring from the superconductors to the cooling environment (assuming that liquid nitrogen is used as cryocoolant). Therefore, the expression of the temperature growth against time is given in (2) [11].

$$T = T_0 + \frac{1}{C} \int E(J, T) \cdot J(t) dt \quad (2)$$

wherein T_0 is the temperature of the liquid nitrogen, and C is the heat capacity of the material per volume. The relationship between the resistance of the superconductor and the electric field and current density can be written in an approximate manner, as in (3) [13].

$$R = \frac{E}{J} \cdot \frac{L}{A} \quad (3)$$

where L and A are the length and cross-sectional area of the superconductor, respectively.

III. TEST SYSTEM

The simulations in this paper were performed by using the software RSCAD [10], which represents the graphical user interface for data entry, interaction and plotting of the RTDS[®]. The VSC-HVDC system used in the study consists of a two terminal system and symmetric monopolar type. It employs two-level converters, with PWM-sinusoidal modulation and control performed in $d-q$ coordinates as presented in [14]. In this condition, a converter controls the DC voltage while the other controls the flow of the active and reactive power. The parameters of the VSC-HVDC system are presented in the Appendix. Fig. 1 illustrates the schematic diagram of the system.

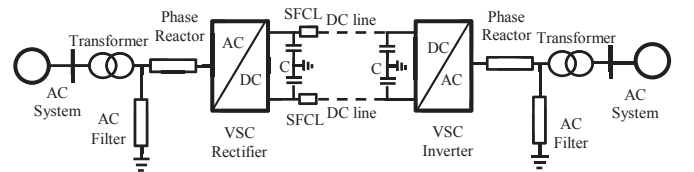


Figure 1. VSC-HVDC system with SFCL.

IV. EFFECTIVE DESIGN OF THE SFCL

In the event of a fault in the DC lines in VSC-HVDC systems composed of two-level converters, the IGBT loses the ability to control and turn off in a short time, but the fault current is not interrupted since the diodes in anti-parallel feed the fault as a traditional bridge rectifier [4-6]. At the same time, the capacitors also feed the fault. Thus, the converter is not able to clear the fault current, which is limited only by the impedance of the

system, causing high currents that can damage the diodes. So, it can be observed that there is a high potential application of SCFL to limit the fault current.

The superconducting material considered in the proposed SFCL here is Bi2223, known as first generation HTS. Bi2223 tape has been commercialized for over ten years, so the technology is relatively mature. The modelling method can also be applied to YBCO, known as second generation HTS, when the parameters are selected accordingly. The parameters E_c , J_c , ρ , T_c and n depend on the intrinsic characteristics of the material. To effectively model a SFCL, we need to introduce two parameters for our modeling: effective length L and effective cross-sectional area A of the superconducting material.

The worst fault condition in the DC line is a fault at the sending end of the line. Fig. 2 shows the equivalent DC diagram for a fault in this condition. In this case, the AC equivalent is represented by a DC voltage source (V_{dc}) in series with a resistance (R_{eq}), which is equal to the absolute value of the equivalent impedance of the AC system divided by three, as the currents of three phases pass through it during faults in the DC line.

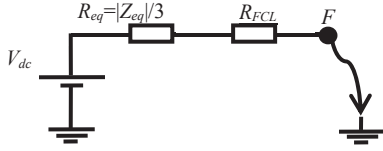


Figure 2. DC short circuit equivalent circuit.

Thus, the short-circuit current can be calculated by (4).

$$I_{sc} = \frac{V_{dc}}{\frac{1}{3}|Z_{eq}| + R_{FCL}} \quad (4)$$

where V_{dc} is the voltage on the DC side before the fault, Z_{eq} is the equivalent impedance in AC side, which considers the phase reactor of VSC, the transformer impedance and the impedance connection to the AC system; and R_{FCL} is the limiter's resistance after the fault, which is the parameter to be estimated, so that the short circuit current does not exceed the desired value. By isolating R_{FCL} from (4) results in (5).

$$R_{FCL} = \frac{V_{dc}}{I_{sc}} - \frac{1}{3}|Z_{eq}| \quad (5)$$

The expression of R_{FCL} in the conducting state is shown in (6).

$$R_{FCL} = \frac{\rho L}{A} \cdot \frac{T}{T_c} \quad (6)$$

For the superconducting material in the conducting state, the ratio T/T_c will always be bigger than unity. Thus, adopting a conservative approach, that ratio will be considered equal to one. Then, the values of L and A should be determined so that the value of R_{FCL} be at least equal to (5). The effective area of the SFCL can be calculated as a function of the critical current (I_c),

as shown in (7). It should be emphasized that the SFCL just leaves the superconducting state if the fault current becomes higher than the critical current. In real design, the effective cross-sectional area A will provide information about how many HTS tapes are required to be connected in parallel for the SFCL.

$$A = \frac{I_c}{J_c} \quad (7)$$

Replacing (7) and (6) in (5) and isolating L , the expression for calculating the effective length of the superconducting material used in the modelling is given by L (8).

$$L = \left(\frac{V_{dc}}{I_{sc}} - \frac{1}{3}|Z_{eq}| \right) \cdot A \cdot \frac{1}{\rho} \quad (8)$$

If the critical current of a SFCL is chosen to be too small, there will be a great possibility of damaging the HTS material during a fault. On the other hand, if the value of the critical current is too high, close to the value of the fault current to be limited, the material will take longer to leave the superconducting state to effectively limit the fault current. Thus, the value of I_c is an important parameter in the SFCL design. By running several simulations, it was observed that if the critical current is equal to half of the current to be limited, the SFCL limits the fault current quickly and efficiently, and the material shows no significant temperature rise.

In this way, the desired fault current is adopted in this work as the DC circuit breaker current limit ($I_{breaker}$) and the critical current is half of this limit. Therefore, the effective area and length of the SCFL are defined by (9) and (10), respectively.

$$A = \frac{1}{2} \cdot \frac{I_{breaker}}{J_c} \quad (9)$$

$$L = \left(\frac{V_{dc}}{I_{breaker}} - \frac{1}{3}|Z_{eq}| \right) \cdot A \cdot \frac{1}{\rho} \quad (10)$$

According to [15] and [16], the fault current levels that can be interrupted by DC circuit breakers are up to 9 kA, considering hybrid DC breakers. Although this level is likely to improve as the technology develops, higher interrupt capabilities will always be more expensive.

V. SIMULATIONS AND RESULTS

This section presents the method results and the results of fault simulations in the VSC-HVDC system of Fig. 1. In order to validate the method presented in the work, three different dimensions of superconducting materials were calculated, resulting in three SFCL. These devices should limit the fault current at 9 kA (FCL1), 6 kA (FCL2) and 3 kA (FCL3), representing the maximum current that can be interrupted by three different DC breakers.

A. Parameters of the SFCL effective model

In this section, the effective area and length calculation of FCL1 is shown. At first, the values of V_{dc} , ρ and J_c are 83 kV, $1 \cdot 10^{-5} \Omega \cdot m$ and $10^8 A/m^2$, respectively. The value of Z_{eq} in this case is the sum of the AC system equivalent impedance (Z_{AC}), the transformer impedance (Z_T) and the impedance of the phase reactor of VSC (Z_{VSC}), as given by (11).

$$Z_{eq} = Z_{AC} + Z_T + Z_{VSC} = 0.075 + j8.2 \Omega \quad (11)$$

For FCL1, the current to be limited is 9 kA. Thus, by replacing all the available parameters in (9) and (10), the values of A and L are found, as presented in (12) and (13). It is important to note that the effective length here is a parameter to be used in the model, and it is not referring to the real length of HTS material required for the SFCL.

$$A = \frac{1}{2} \cdot \frac{9 \cdot 10^3}{10 \cdot 10^7} = 4.5 \cdot 10^{-5} m^2 \quad (12)$$

$$L = \left(\frac{83 \cdot 10^3}{9 \cdot 10^3} - \frac{1}{3} \cdot 8.24 \right) \cdot 4.5 \cdot 10^{-5} \cdot \frac{1}{1 \cdot 10^{-5}} = 29.5 m \quad (13)$$

Similarly, the same procedures were applied to calculate the SFCL2 and SFCL3 effective parameters, but in such cases the current $I_{breaker}$ is 6 kA and 3 kA, respectively. Table I summarizes the results of the design methodology for the three cases considered.

TABLE I. SUMMARY OF EFFECTIVE PARAMETERS.

FCL	$I_{breaker} [kA]$	$L [m]$	$A [cm^2]$	$V [cm^3]$
FCL1	9	29.5	0.45	1327.5
FCL2	6	33.5	0.3	1005
FCL3	3	37.5	0.15	562.5

B. Fault simulations and method validation

In order to validate the results of Table I, pole to ground faults were simulated between the limiter and the DC line without fault resistance. The fault was applied at 0.02 second.

Fig. 3 shows the fault current for four cases. The blue curve shows the fault current when the system operates without the SFCL. In this situation the current (I_{sc}) exceeds 25 kA. The other curves (I_{scFCL1} , I_{scFCL2} , I_{scFCL3}) represent the system response for the same type of fault, but considering the system with SFCL in series with the line. Additionally, the current limits (breaker capability) of the circuit breakers are shown in Fig. 3.

The results presented in Fig. 3 show the effectiveness of the use of the SFCL in mitigating the impacts of faults in VSC-HVDC lines, validating the proposed SFCL effective model. Notice that the fault currents exceed the interruption current capacity of the breakers for a short period of time, and after this, the breakers are able to disrupt the fault current.

As the fault current levels were significantly reduced, the protection of the VSC-HVDC lines have more time to operate,

which facilitates the protection coordination. Additionally, the protection system does not need to operate for temporary faults, which may occur, especially for overhead lines, decreasing the time that the system is out of service.

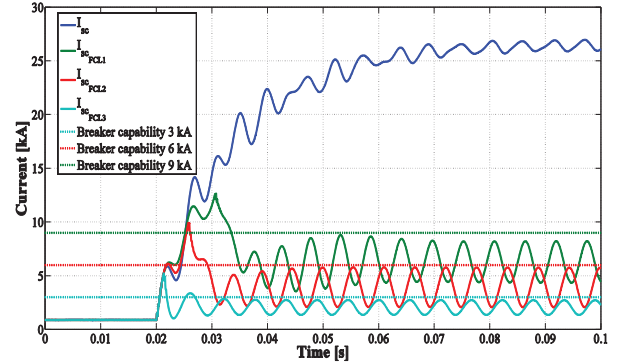


Figure 3. Fault currents for different SFCL effective parameters.

Fig. 4 shows the resistance values of FCL1 (R_{FCL1}), FCL2 (R_{FCL2}) and FCL3 (R_{FCL3}) during the fault. The highest resistance (R_{FCL3}) is related to SFCL3, because in this case the DC breaker limit is 3 kA – the smallest current among the cases analyzed. Thus, in this situation the critical current is 1.5 kA, making the SFCL to leave the superconducting state faster than SFCL1 and SFCL2.

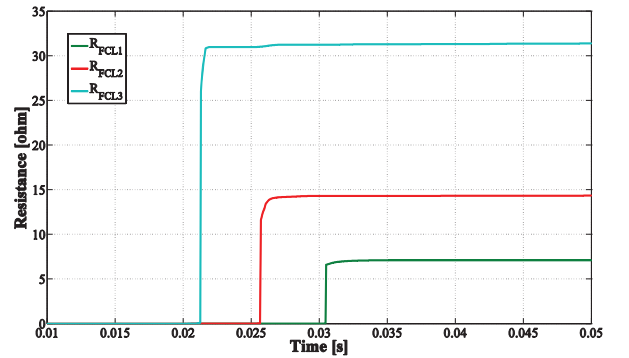


Figure 4. Resistance behavior.

Fig. 5 illustrates the temperature increase for FCL1 (T_{FCL1}), FCL2 (T_{FCL2}) and FCL3 (T_{FCL3}). Note that, even FCL3 being more effective than others, the temperature reached by such material is lower than the temperature reached by SFCL2. In all the three cases, the temperature rise is small when compared with the results of [8] and [12], in which the temperature exceeds 400 K. This validates the choice of the critical current value used in this analysis.

Table II shows the temperature values reached after 50 ms and the reduction of the fault current after 60 ms, which is compared with the fault current without SFCL. It can be observed that the percentage of the fault current reduced by FCL2 is smaller than the obtained by using FCL3, but the FCL2 temperature reached higher values.

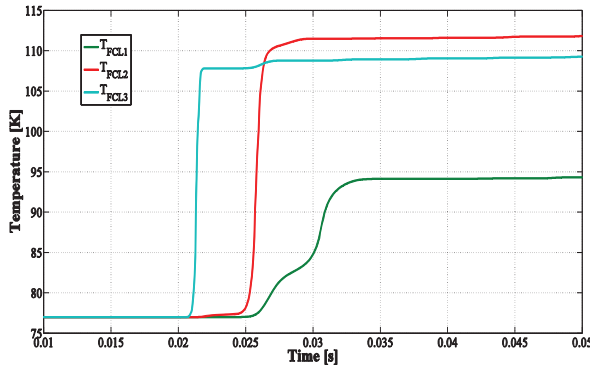


Figure 5. Temperature rise during the fault.

TABLE II. SUMMARY OF RESULTS.

FCL	$I_{breaker}$ [kA]	T [K]	I_{sc} reduction [%]
FCL1	9	95	69
FCL2	6	112	78.5
FCL3	3	109	90

¹Values at 50 ms. ² Max average values after 60 ms.

Table I shows that the FCL3 has the longest effective length among the three considered SFCL; however, its effective volume is smaller than the other SFCLs, which can reduce the costs of this material. Similarly, the cost of the circuit breaker in this case is also lower, since the maximum current that can be interrupted by the circuit breaker is the smallest in comparison with the other circuit breakers. Therefore, the choice of FCL3 represents the best technical and financial choice among the three cases analyzed, since the fault current has been limited up to 90% compared to the base case, as shown in Table II.

Another advantage of using FCL3 is that the protection system has more time to operate. This characteristic can improve the operating performance of multi-terminal VSC-HVDC systems, because it increases the protection selectivity.

VI. CONCLUSION

This work presented a simplified method for obtaining an effective model of an SFCL used in VSC-HVDC systems, considering the DC breakers overcurrent withstand capability. The method was validated by time domain simulations undertaken with the RTDS®, and the results showed that the fault current could be reduced up to 90%. Therefore, the proposed method is quite effective and it highlights the importance of considering the breaker capability in analyzing the SFCL performance. Further steps include the investigation of the effectiveness of the proposed method to other VSC-HVDC system topologies. In addition, the economic feasibility of the use of superconducting materials applied in VSC-HVDC systems will be evaluated.

VII. APPENDIX

SFCL parameters:

- $T_0 = 77$ K, $T_c = 87$ K, $J_c = 10^8$ A/m², $E_c = 0.0001$ V/m, $n = 10$, $\rho = 1 \cdot 10^{-5}$ $\Omega \cdot m$, $C = 0.1$ M/m³.

VSC-HVDC system parameters:

- $P_{dc} = 150$ MW, $V_{dc} = 83$ kV, $I_{dc} = 890$ A, $V_{ac} = 100$ kV
- DC line: length = 100 km (Bergeron model with 2 sub-conductors; sub-cond radius = 1.04 cm; sub-cond spacing = 50 cm; Horiz. Dist. X = 7.5 m; Height at Tower Y = 35 m; Sag at Midspan = 10 m; DC resistance per Sub-Cond = 0.03206 Ω/km ; Ground resistivity = 100 $\Omega \cdot m$).
- DC side capacitance of VSC, $C = 70$ μF .
- Phase reactor = 0.075 $\Omega + 20$ mH.
- Smoothing reactor = 8 mH.
- PWM switching frequency is 1980 Hz.

AC System parameters:

- Transformers: Yg-Yg connection, with $Z_T = j0.5$ Ω .
- Connection impedance on the Rectifier side: $Z_{ACr} = j0.2$ Ω
- Connection impedance on the Inverter side: $Z_{ACi} = j0.4$ Ω

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